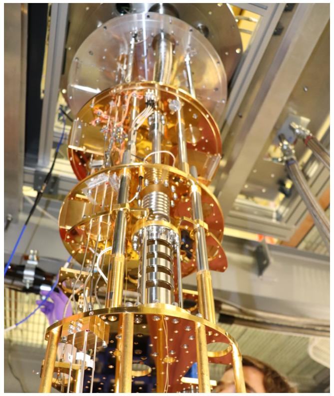
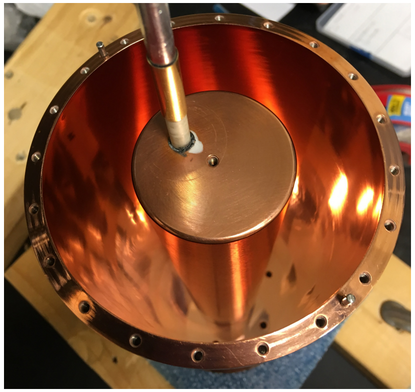
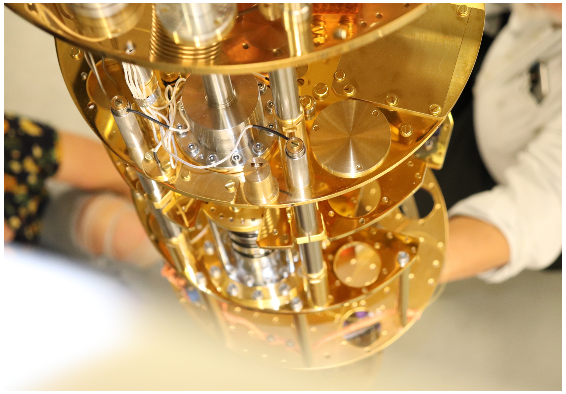
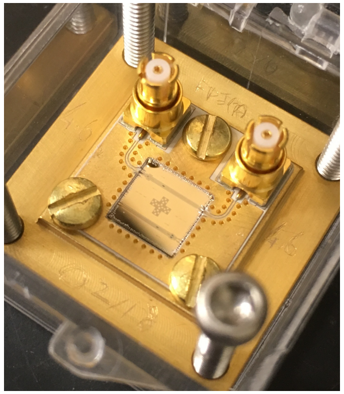
Speeding up the Search for Axions with Quantum Squeezing









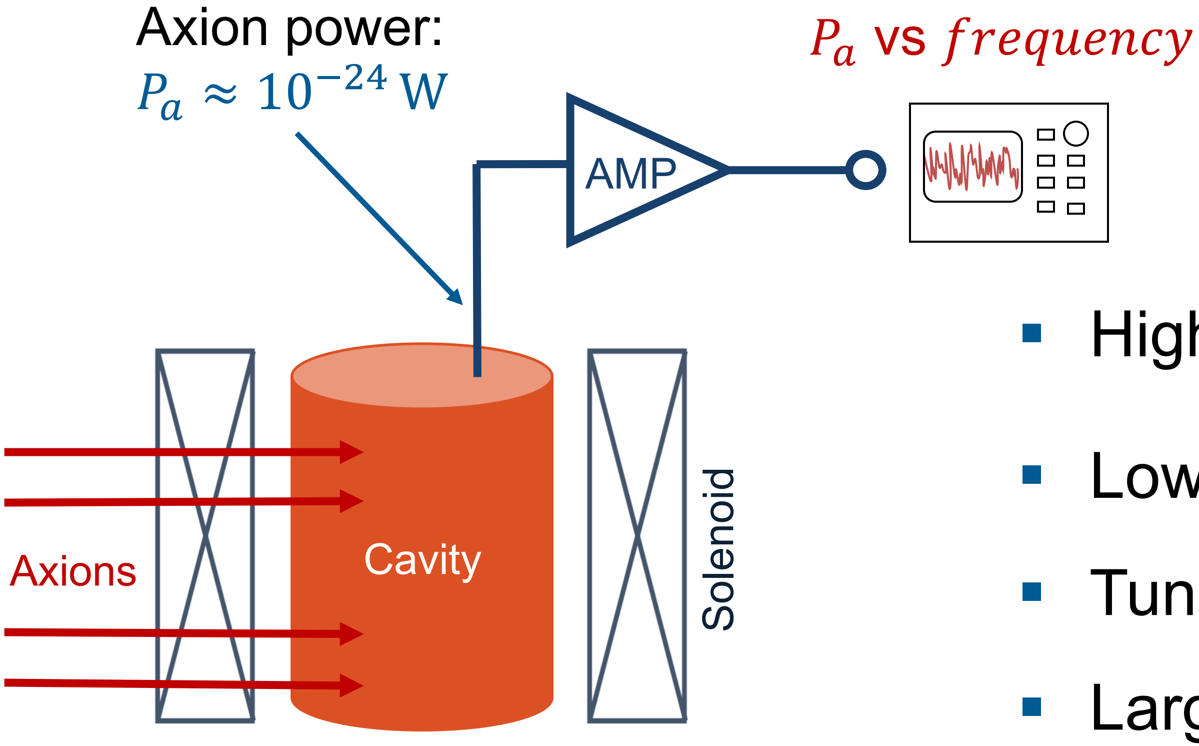
Kelly Backes

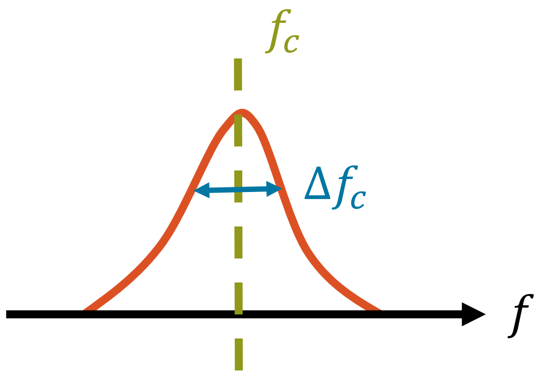
CPAD

March 22, 2021

The Haloscope Detection Scheme

Interaction: $\mathcal{L} \supset g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$





- High Q cavity: $Q = \frac{f_c}{\Delta f_c}$
- Low noise amplifier
- Tunable: $hf_a \approx m_a c^2$
- Large magnet: $\boldsymbol{B} = 8\ \mathrm{T}$
- Cryogenic: $T = 60\ \mathrm{mK}$

haloscope principle: P. Sikivie, *Phys. Rev. Lett.*, **51**, 1415 (1983)

Haloscope Figures of Merit

Figures of merit:

- Signal to noise ratio: $\mathrm{SNR} = \frac{P_a}{N_S}\sqrt{\frac{\tau}{\Delta f_a}}$
- Scan rate: $R \propto \int \mathrm{SNR}(f)^2$

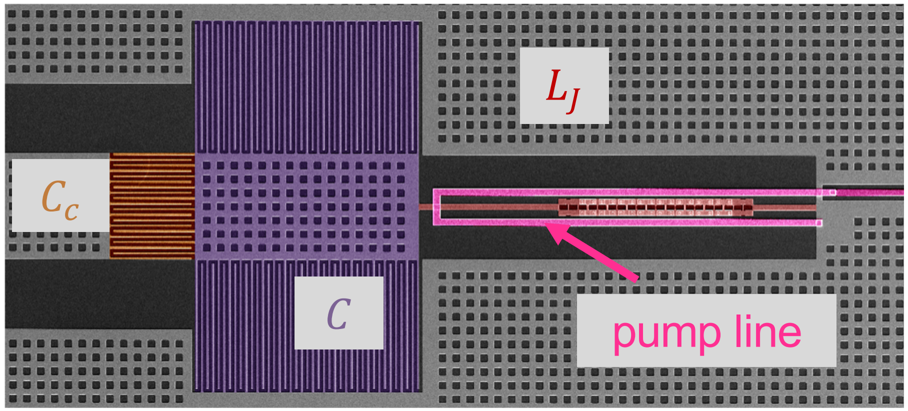
Frequency scaling:

- Decreased signal power: $P_a \propto QV$
- Effective scan rate scaling: $R \propto \nu^{-14/3}$

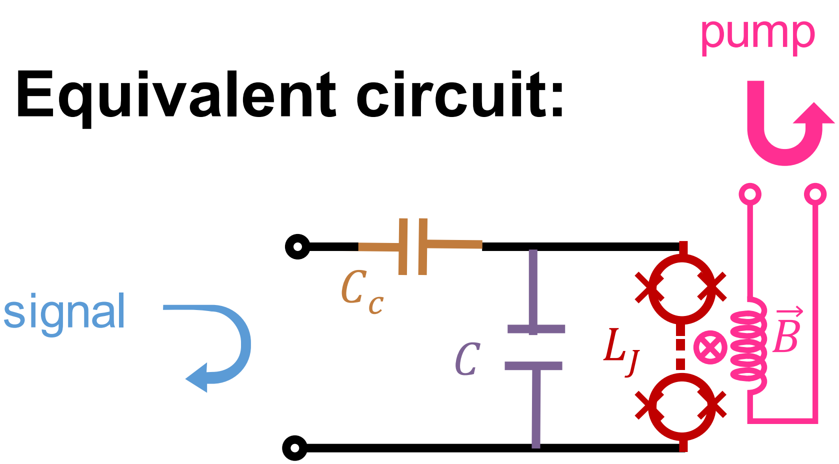
$f \approx 5\ \mathrm{GHz}$

Josephson Parametric Amplifiers (JPAs)

Image:



Equivalent circuit:

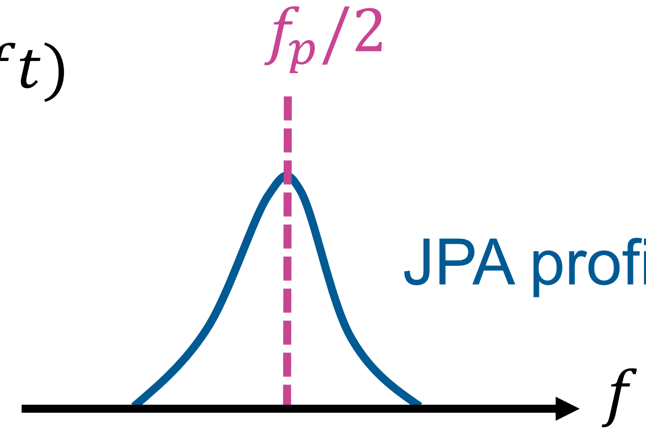


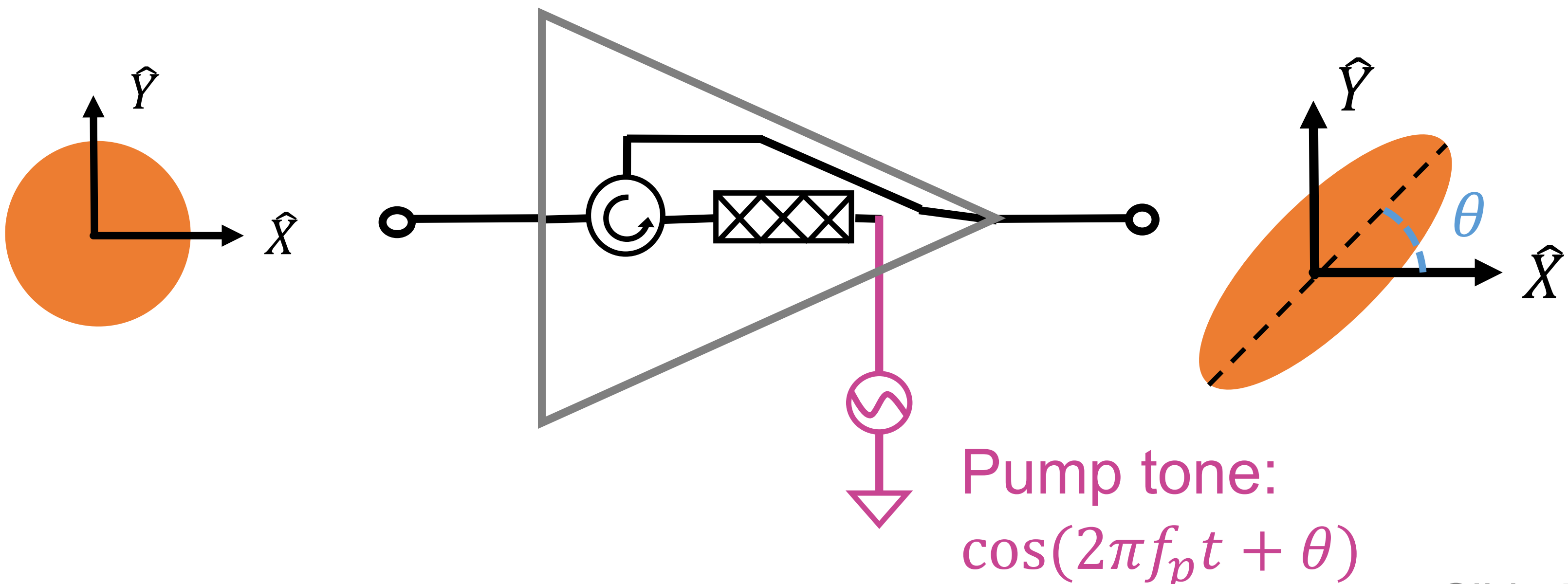
- Tunable LC resonator
- Inductance from SQUIDs
- $\omega_0 = 1/\sqrt{LC}$

JPAs Source Squeezed States

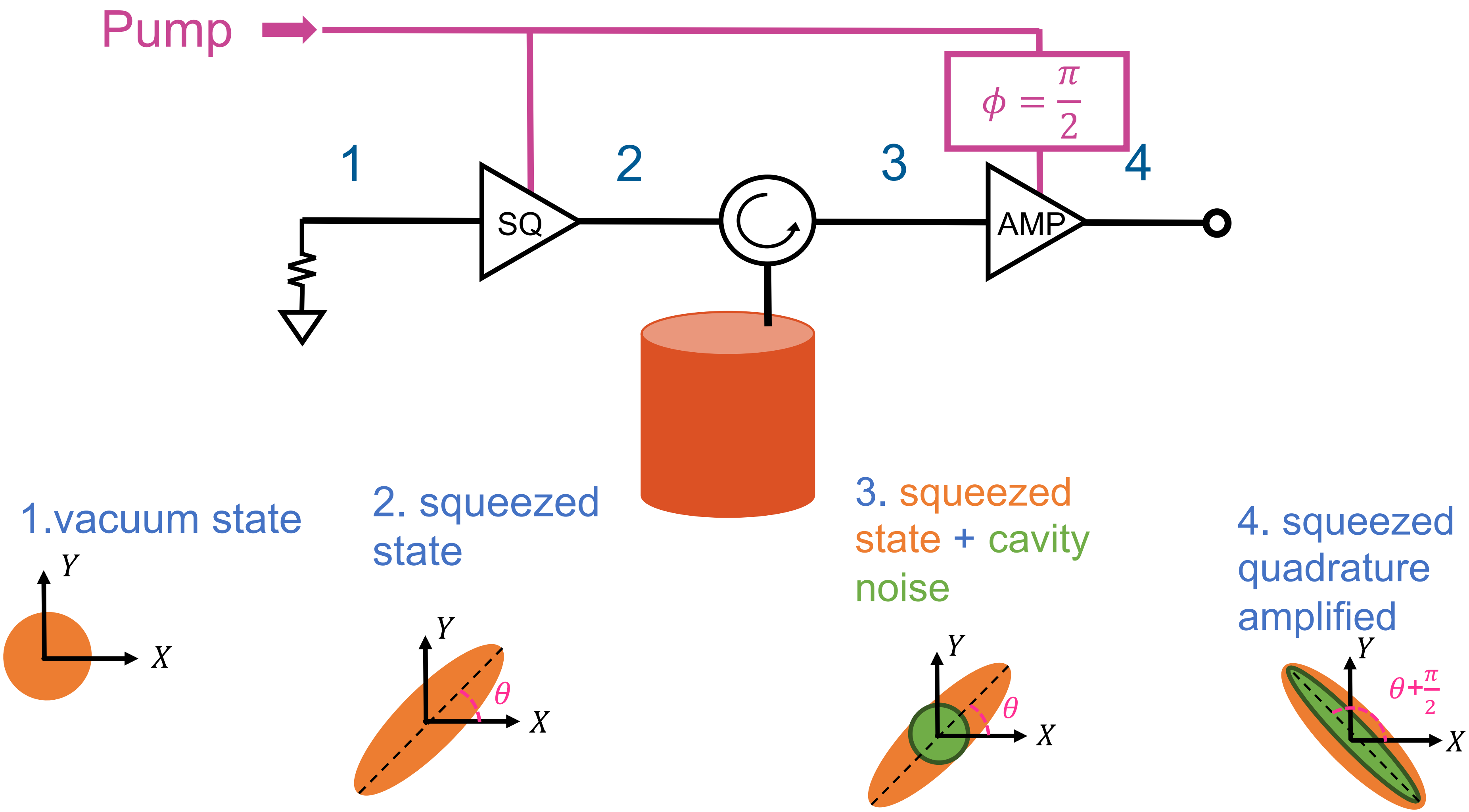
Signal: $\hat{V} = \hat{X}\cos(2\pi f t) + \hat{Y}\sin(2\pi f t)$

Uncertainty: $\sigma_{\hat{X}}^2 \sigma_{\hat{Y}}^2 \geq \frac{1}{4}$

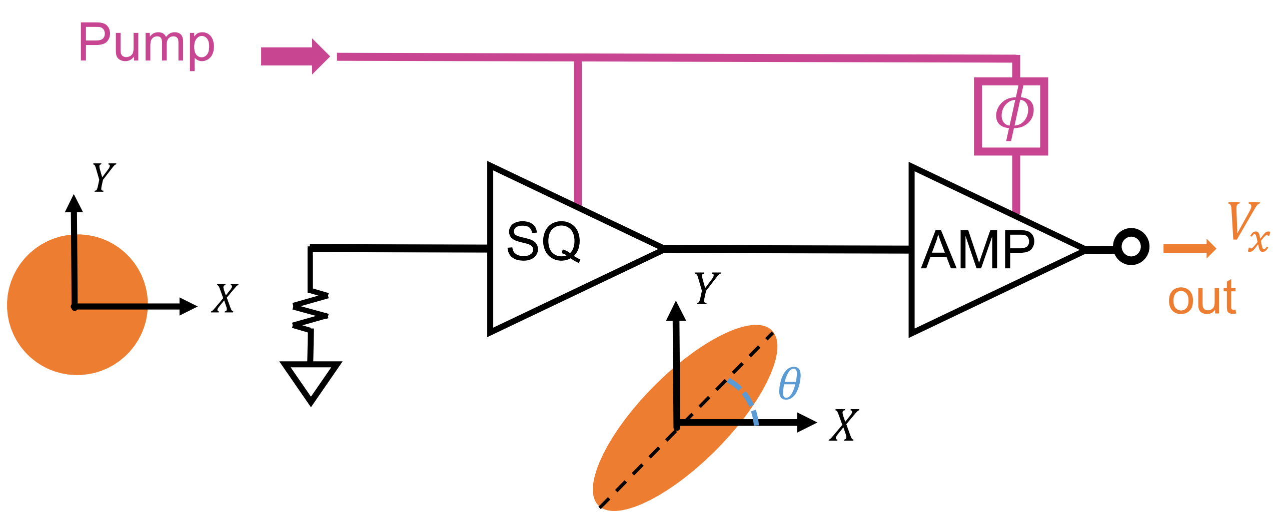




Squeezed State Receiver Operation

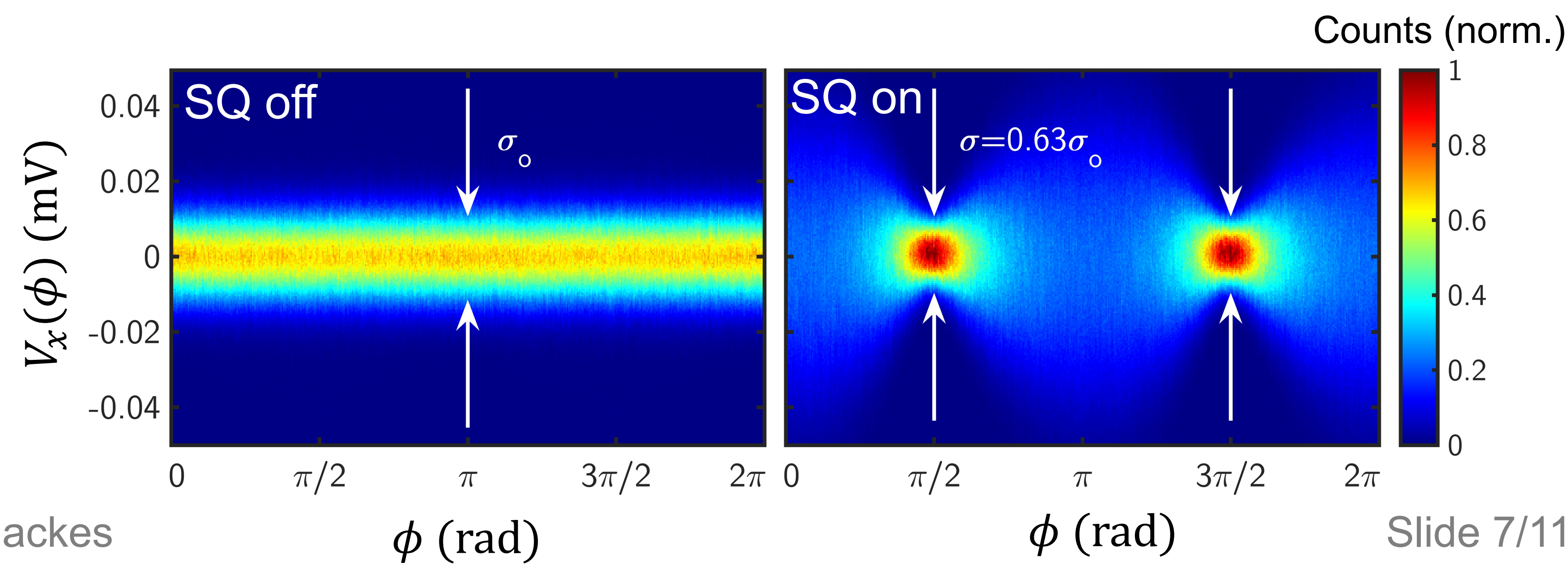


Measured Noise Reduction

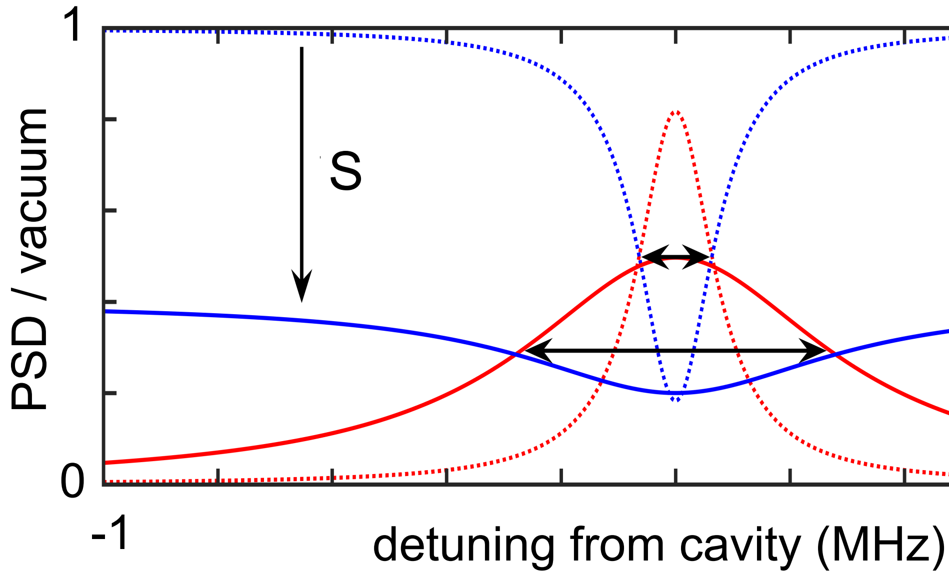


S = $\frac{\sigma_{on}^2}{\sigma_{off}^2} = 4.0$ dB

Speedup = $1.9\times$



Squeezed State Receiver Benefit



Reflected noise reduction:

S = 4.0 dB

Scan rate:

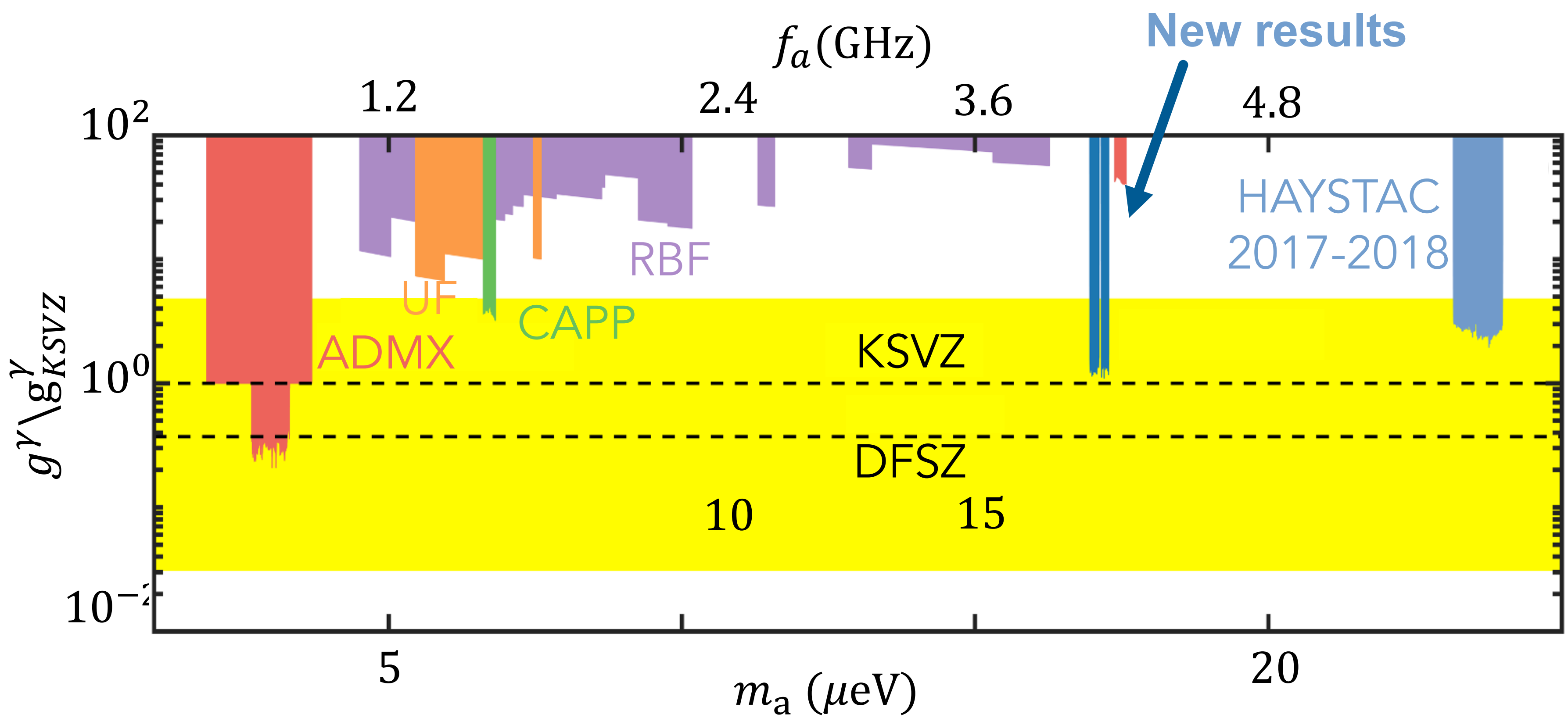
$$R \propto \int \mathrm{SNR}(f)^2$$

cavity noise
reflected noise
SQ off, $2.0\times$ overcoupled

cavity noise
reflected noise
SQ on, $7.1\times$ overcoupled

Most sensitive axion search > $10\ \mu eV$

First dark matter exclusion enhanced by quantum squeezing



results: K.M. Backes *et al.*, arxiv.org:2008.01853

Conclusion

- Excluded 70 MHz of axion parameter space at $1.38\times g^{\gamma}_{KSVZ}$
- First quantum squeezed state enhanced run is complete
- Doubled data collection rate with quantum squeezing

Thanks:

JILA CU Boulder and NIST

Wright Laboratory

NSF

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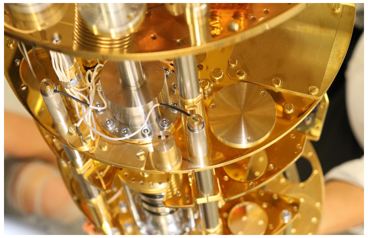
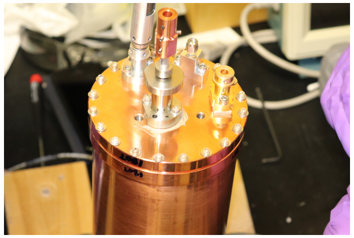
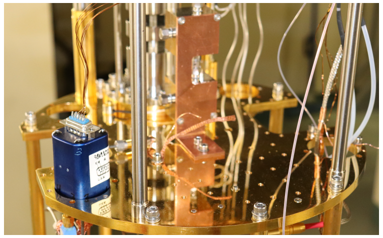

Further reading:

Squeezing results: arxiv.org:2008.01853 (2020)

Bayesian analysis: Phys. Rev. D, **101**, 123001 (2020)

Squeezed state receiver: Phys. Rev. X **9**, 021023 (2019)

Analysis: Phys. Rev. D 96, 123008 (2017)

First results: Phys. Rev. Lett. 118, 061302 (2017)

Instrumentation: Nucl. Instrum. Methods A 854, 11 (2017)

Thank you!

Haystac

JILA CU Boulder and NIST

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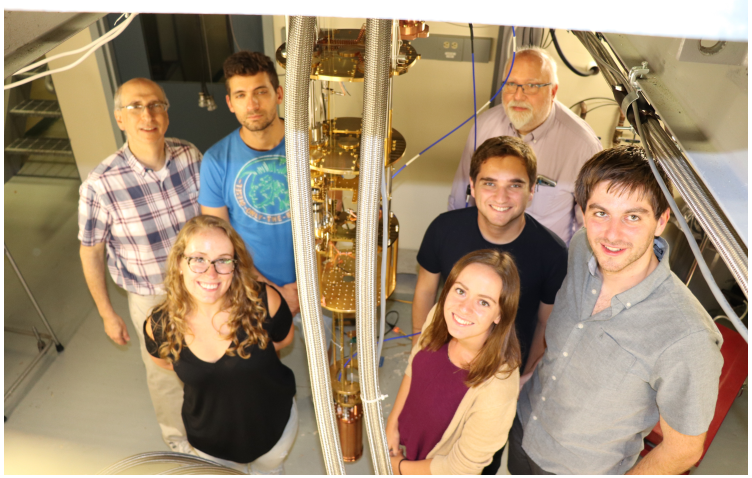

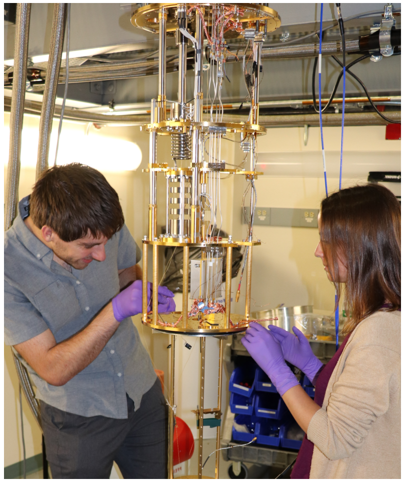

Funding:

NSF

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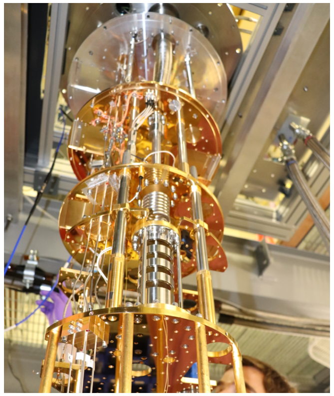
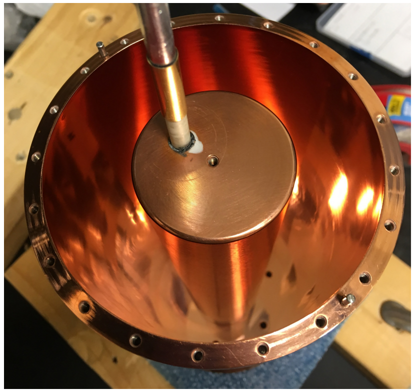
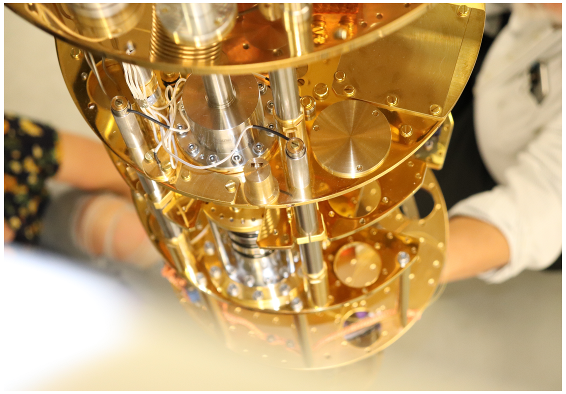
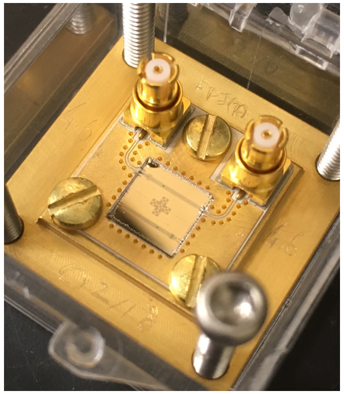
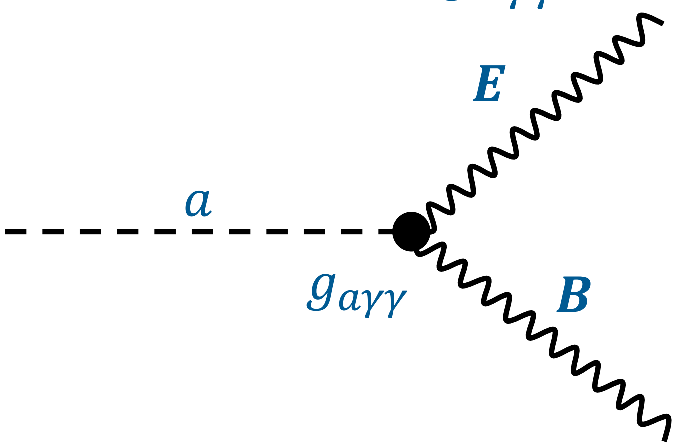
Backup Slides

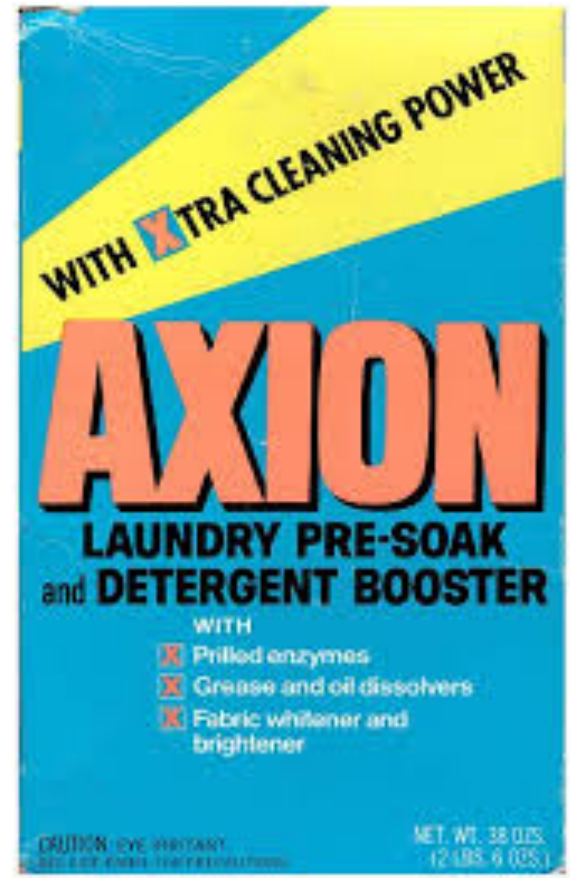






The Axion: A Well-Motivated Solution

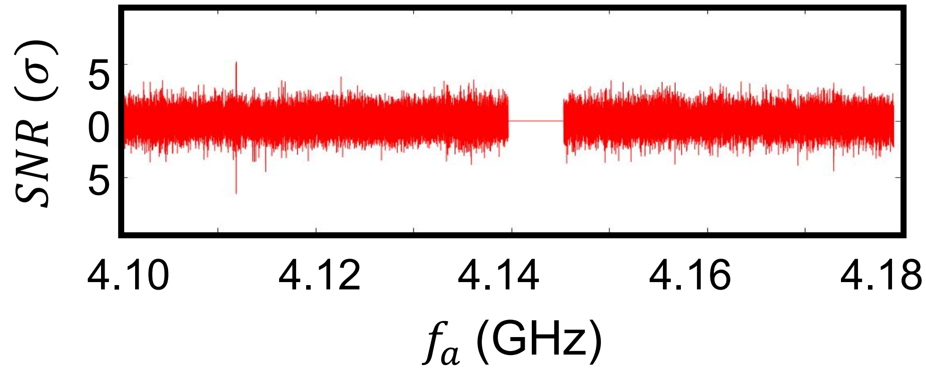
- Strong CP problem solution: $\Theta \propto a(x)$
- Lifetime: $L >$ current age of universe
- Couples weakly: $m_a \propto g_{a\gamma\gamma}$
- Interaction: $\mathcal{L} \supset g_{a\gamma\gamma} a\boldsymbol{E}\cdot\boldsymbol{B}$



- Acts like a classical field: $hf_a \approx m_a c^2$



Applying the Bayesian Analysis



Prior update:

$$U(\sigma) = \frac{P(\sigma|\text{axion})}{P(\sigma|\text{no axion})}$$

- Calculate U for each measured power
- Determine U = 0.1 at each frequency